Hydrobiology

ACID MINE DRAINAGE (AMD) – REVIEW OF CADIA VALLEY OPERATIONS ENVIRONMENTAL MONITORING PROGRAM DESIGN AND DATA

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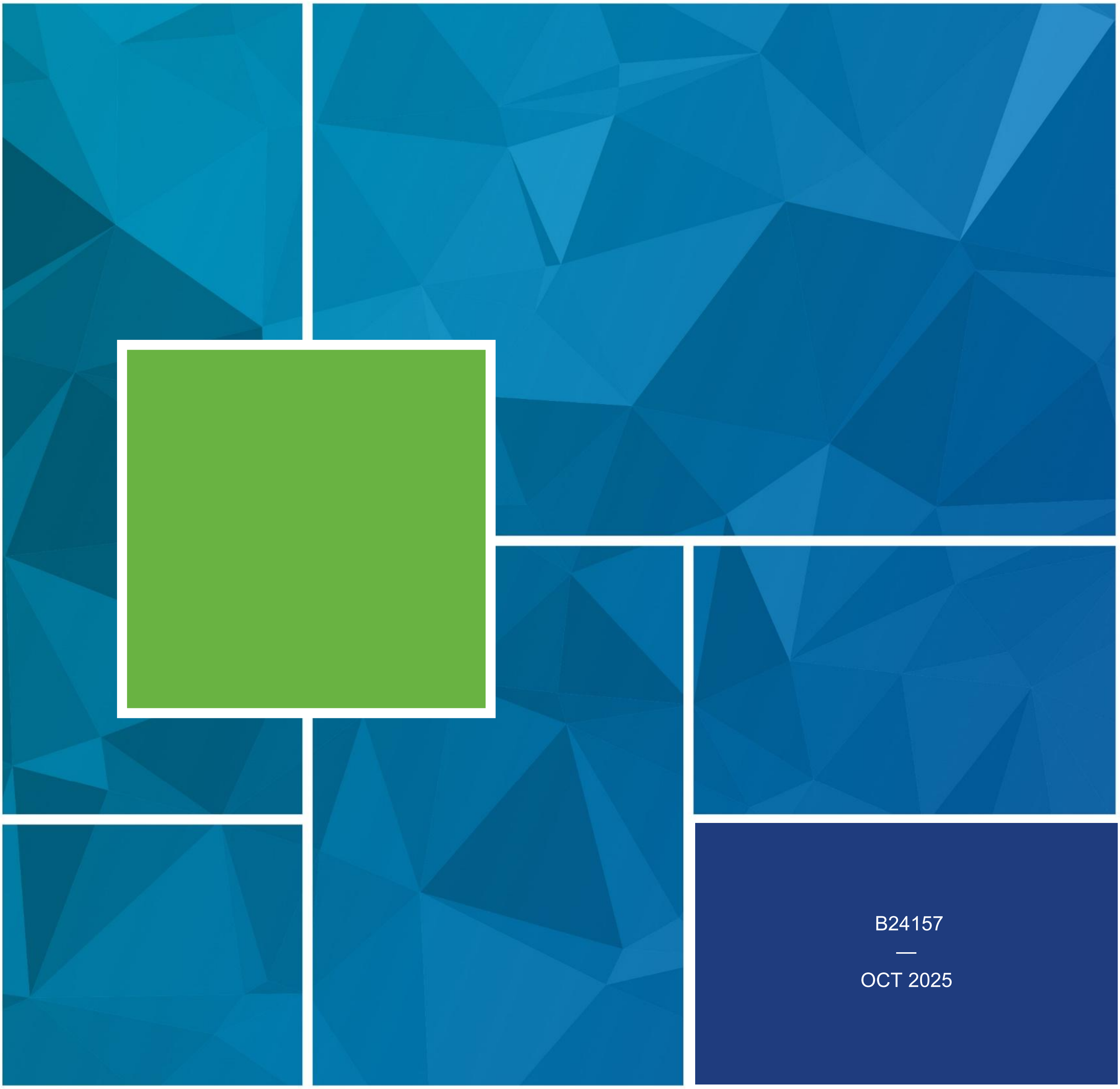
PREPARED FOR THE NSW EPA



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1.

INTRODUCTION

1.1 SCOPE

The NSW Environment Protection Authority (EPA) requested Hydrobiology to provide additional specific consideration of Acid Mine Drainage (AMD) as part of the *Review of Cadia Valley Operations (CVO) Environmental Monitoring Program Design and Data* (the Report).

This Addendum has been prepared by Hydrobiology in response to that request and is intended for public release alongside the original Report. The purpose of this Addendum is to review available monitoring data and site information to determine whether AMD processes are evident, effectively managed, or require further monitoring consideration at CVO.

The scope of this Addendum specifically addresses the following questions outlined by the EPA:

1. Was Acid Mine Drainage (AMD) considered as a potential pollution indicator in Hydrobiology's assessment and Report?
2. Do the existing monitoring results indicate that AMD is occurring at the CVO site or in receiving groundwaters or surface waters?
3. Does mine dewatering effectively capture and treat any acid potentially generated from underground operations or key infrastructure?
4. Does Hydrobiology have any recommendations in relation to the existing monitoring program for AMD at CVO?

To address these questions, Hydrobiology has undertaken a focused review of existing surface water, groundwater, and mine dewatering datasets, together with relevant site and geochemical information. Recommendations are provided where appropriate to enhance the detection and management of AMD within the existing monitoring framework.

1.2 ACID MINE DRAINAGE / ACID AND METALLIFEROUS DRAINAGE (AMD)

Acid Mine Drainage (AMD), more broadly referred to as Acid and Metalliferous Drainage (AMD) or Acid Rock Drainage (ARD), describes the generation of acidic and metal-rich water as a result of the oxidation of sulfide-bearing minerals such as pyrite (FeS_2), pyrrhotite ($Fe_{1-x}S$), and chalcopyrite ($CuFeS_2$). When these minerals are exposed to oxygen and water through mining or excavation, oxidation reactions, usually bacterially mediated, produce sulfuric acid and mobilise metals and metalloids from surrounding rock materials (DITR, 2007; INAP, 2014). This process can lead to the formation of highly acidic, sulfate-enriched drainage with elevated concentrations of dissolved metals such as Fe, Al, Cu, Zn, Ni, and Mn (Blowes et al., 2014).

AMD is widely recognised as one of the most substantial and long-term environmental challenges associated with mining and mineral processing activities. The production of acidic drainage and associated metal mobilisation can cause severe impacts on water quality, loss of aquatic and terrestrial biodiversity, degradation of soil and vegetation, and long-term contamination of groundwater and surface water systems (DITR, 2007; ANZG, 2018). Moreover, unmanaged AMD can have major implications for mine closure planning, rehabilitation costs, and the social licence to operate, as communities and regulators increasingly demand proactive environmental stewardship in mine-affected areas (INAP, 2014).

Modern frameworks use the broader term *Acid and Metalliferous Drainage* to encompass a spectrum of mine-influenced drainage types (Table 1-1), including:

- Acidic drainage ($pH < 5$), where oxidation exceeds neutralisation capacity;
- Neutral mine drainage (NMD), where sulfide oxidation occurs but is buffered by carbonate or silicate minerals, resulting in circumneutral pH yet elevated sulfate and dissolved metals; and
- Saline or metalliferous drainage, characterised by high total dissolved solids (TDS) and metal/metalloid concentrations under neutral or alkaline pH (DITR, 2007; ANZG, 2018).

The key monitoring parameters for AMD assessment in water quality programs include:

- pH (as an indicator of acidity or buffering),
- Acidity and alkalinity, which together define net acid–base status,
- Electrical conductivity (EC) and sulfate, reflecting salinity and oxidation intensity, and
- Dissolved and total metals, which identify leaching or precipitation processes relevant to site geochemistry.

Interpreting AMD-related data requires a holistic and contextual approach rather than relying on single-parameter exceedances. Indicators should be assessed collectively to determine the presence or risk of AMD, incorporating:

- Comparative analyses with background or reference site data and temporal trends;
- Use of correlation plots (e.g., pH vs SO_4^{2-}, Fe vs SO_4^{2-}, Al vs pH) to identify oxidation–neutralisation relationships; and

- Application of geochemical modelling tools such as *Geochemist's Workbench (GWB)* or *PHREEQC* to validate observed patterns and quantify saturation or redox equilibria where sufficient data exist.

Thresholds or interpretive limits should be treated as indicative only and refined using site-specific baseline datasets and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG, 2018) to reflect local mineralogy, hydrogeology, and historical mine influences.

Table 1-1 AMD Identification Criteria and Interpretation

Category	Parameter / Ratio	Indicative Threshold / Range	Interpretation / Evidence of AMD	Comments / Notes
Field Parameters	**pH**	< 5.0 = Strong indicator; 5–6 = Moderate	Acidic conditions typical of AMD; neutral to slightly acidic may indicate partial neutralisation.	Evaluate spatially (pit, seepage, downstream).
	Electrical Conductivity (EC)	> 1,000 µS/cm (site-specific)	Elevated salinity from dissolved ions (SO_4^{2-}, Fe^{2+}, metals).	Correlate with pH, sulfate and metals.
	Redox potential (Eh)	> +300 mV (oxidising)	Reflects sulfide oxidation processes.	Oxidising conditions promote AMD.
Major Ions	**Sulfate (SO_4^{2-})**	> 100 mg/L (background-adjusted)	Key product of sulfide oxidation.	High sulfate with low pH = active AMD.
	Alkalinity vs Acidity balance	Net Acidity > 0 mg/L $CaCO_3$	Acid generation exceeds neutralising capacity.	Derived from titration data.
Metals (Dissolved / Total)	**Iron (Fe^{2+} / Fe^{3+})**	> 1 mg/L (Fe total)	Indicates pyrite oxidation and iron cycling.	$Fe^{3+}:Fe^{2+} > 1$ → oxidising AMD conditions.
	Aluminium (Al)	> 0.5 mg/L	Mobilised under low pH (< 5).	Often co-elevated with Fe.
	Manganese (Mn)	> 0.3 mg/L	Soluble under acidic or reducing conditions but can be kinetically slow to precipitate under neutral oxic conditions. Can be a tracer for AMD after neutralisation.	Tracks secondary redox fronts.
	Trace metals (Cu, Zn, Pb, Ni, Co, Cd)	Above background or WQOs	Released under low-pH conditions. May assist with source identification depending on local geology.	Compare with upstream controls.
Ratios & Relationships	**Fe : SO_4 molar ratio**	~ 0.5 for pyrite oxidation	Deviation suggests mixed sources or secondary processes.	Use for source identification.
	pH vs metal correlations	Negative slope (metals ↑ as pH ↓)	Diagnostic of AMD mobilisation.	Plot Fe, Al, Mn, Zn against pH.
Visual / Field Evidence	**Precipitates, staining, water colour**	Orange/yellow ($Fe(OH)_3$), jarosite)	Surface expression of AMD.	Verify against field photos and logs.

Category	Parameter / Ratio	Indicative Threshold / Range	Interpretation / Evidence of AMD	Comments / Notes
	Biological indicators	Reduced macroinvertebrates or algal growth	Ecological response to acidity and metals.	Qualitative support evidence.

2.

METHODOLOGY

This assessment was undertaken to evaluate the potential occurrence and expression of Acid and Metalliferous Drainage (AMD) or Neutral Mine Drainage (NMD) processes across the Cadia Valley Operations (CVO) monitoring network. The investigation integrated long-term surface water and groundwater quality datasets collected between 2013 and 2024.

The methodology adopted follows internationally recognised best-practice frameworks, including the *Managing Acid and Metalliferous Drainage* (DITR, 2007) and *Global Acid Rock Drainage (GARD) Guide* (INAP, 2014), as well as the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZG, 2018). The approach combined statistical trend evaluation, geochemical interpretation, and indicator-based screening to determine whether any sites exhibit AMD-related behaviour or neutralised mine drainage conditions.

Water quality data were sourced from CVO's routine environmental monitoring program, including both surface water and groundwater monitoring networks. All data were subjected to preliminary QA/QC screening, including checks for completeness, detection limit consistency, and removal of obvious outliers. Where relevant, below-LOR values were substituted using half the reporting limit for trend visualization purposes (consistent with ANZG, 2018).

The analysis focused on identifying temporal and spatial patterns in key Acid and Metalliferous Drainage (AMD) diagnostic parameters, including pH, acidity, alkalinity, EC, TDS, sulfate, and dissolved metals such as Fe, Al, Mn, Cu, Zn, Mo, Ni, Co, and As. These parameters were selected based on their geochemical relevance to AMD generation and neutralisation processes, representing indicators of acid–base balance, sulfide oxidation, and metal mobilisation. The assessment utilised the time-series plots presented in the main CVO Environmental Monitoring Program Review Report (Hydrobiology, 2025) to evaluate long-term temporal trends and spatial variations at each monitoring location. These plots enabled identification of co-occurring changes in pH, sulfate, EC, and metal concentrations, providing a visual framework for determining whether any sites exhibit chemical signatures consistent with active AMD, neutral mine drainage (NMD), or other forms of mine-influenced water.

Interpretation of AMD indicators was undertaken collectively rather than by individual exceedance, with emphasis on understanding relationships between oxidation, neutralisation, and metal mobilisation processes. Correlation assessments (e.g., pH vs SO_4^{2-}, Fe vs SO_4^{2-}, Mn vs pH) were used to identify geochemical linkages between sulfide oxidation and carbonate buffering. Patterns in Fe, Al, and Mn were evaluated as indicators of redox dynamics and acid solubility, while trace metals such as Cu, Zn, Mo, Ni, Co, and As were reviewed for signatures of either acid leaching or neutral geogenic mobilisation. Comparative assessment between surface and groundwater datasets, and across TSF zones, provided insight into possible hydraulic connectivity and mine-influenced recharge pathways.

Interpretations were validated through cross-checking of chemical relationships, review of supporting alkalinity and sulfate data, and reference to established geochemical models and frameworks (DITR, 2007; INAP, 2014; ANZG, 2018). The classification of drainage type at each site—acidic or neutralised, was guided by these integrated lines of evidence, ensuring that findings reflect both the hydrochemical behaviour and long-term stability of the system rather than isolated analytical events.

3.

RESULTS

This section presents the results of the assessment undertaken to evaluate the potential for AMD and/or NMD across the CVO monitoring network. The evaluation focused on identifying temporal and spatial trends in key AMD diagnostic parameters, including pH, acidity, alkalinity, EC, TDS, sulfate, and dissolved metals. The results are presented by major site group — Cadia Hill Pit, TSFEZ, TSFSZ, and TSFWZ — with integrated interpretation of both surface and groundwater data.

The following subsections summarise the observed water quality trends and interpret the geochemical behaviour in relation to AMD indicators. Each area assessment concludes with an evaluation of whether AMD, NMD, or other mine-influenced drainage processes are currently evident within the monitoring network.

3.1 CADIA HILL PIT

The evaluation included time-series data for key AMD indicators across surface water sites (CAWS46 and CAWS65) and groundwater bores (MB91–MB95, MB30, PZ4, and PZ5) located within and around the Cadia Hill Pit area.

Surface Water

Across both surface water sites, pH has remained circumneutral throughout the monitoring period, ranging between approximately 6.5 and 8.5. Bicarbonate and total alkalinity have been consistently positive, indicating that buffering capacity is maintained and excess acid generation has not occurred. There are no instances of pH falling below 5.0, and the overall pH–alkalinity relationship suggests a neutral to mildly alkaline system. This indicates that any potential acidity generated through sulfide oxidation is effectively neutralised by carbonate reactions within the system.

The influence of tailings deposition within the Cadia Hill Pit is evident in the water quality results for CAWS65, which monitors standing water retained inside the pit. This site reflects the quality of mine affected water retained on site. Sulfate concentrations showed moderate to strong elevation, particularly at CAWS65, with an increasing trend observed after approximately 2018. EC and TDS increased concurrently with sulfate, and these parameters exhibited a strong positive correlation, implying a common geochemical source. The relationships between sulfate, EC, and TDS suggest oxidation of sulfur-bearing minerals has occurred but under conditions where buffering processes have neutralised any associated acidity. This points to the production of NMD rather than AMD.

Fe and Al concentrations were generally low or near detection limits, with only isolated minor elevations in early years of monitoring at CAWS46. Mn concentrations, although measurable, showed a clear declining trend over time, stabilising at concentrations below 1 mg/L in recent samples. The lack of sustained enrichment in Fe, Al, or Mn and the absence of low pH values confirm that active net acid-driven metal mobilisation is not occurring.

Concentrations of Cd, Co, Cu, Mn, Ni, Se, and Zn were generally higher at CAWS46 prior to 2018, followed by a steady decline over time. In contrast, CAWS65 exhibited a gradually increasing trend in certain metals, particularly Sb, As, and Mo. The early elevated metal concentrations at CAWS46 likely reflected historical sulfide oxidation or localised mine-water influence; however, the concurrent neutral pH and measurable alkalinity indicated that any acid generation was effectively neutralised, preventing the mobilisation of acidic conditions. The declining metal trends after 2018 suggested geochemical stabilisation and reduced metal mobility, consistent with NMD behaviour rather than active AMD.

Groundwater

Groundwater quality across monitoring bores MB91–MB95, MB30, PZ4, and PZ5 exhibited similar patterns to surface waters, with circumneutral to mildly alkaline pH (approximately 6–8) and consistently positive alkalinity. No periods of sustained acidity (<5.5) or negative alkalinity were recorded, indicating the absence of net acid generation within the subsurface environment. Variability in alkalinity between bores (higher in MB91–MB94 and lower in PZ4–PZ5) reflected natural spatial heterogeneity in buffering mineral content rather than AMD development.

Sulfate concentrations in groundwater showed an increasing trend in several bores (notably MB93–MB95) beginning around 2018, accompanied by elevated EC and TDS. EC values reached up to approximately 4,500 µS/cm and sulfate up to 1,000 mg/L at some locations. These correlated increases are characteristic of water influenced by sulfide oxidation or AMD interaction; however, the stable neutral pH and persistent alkalinity indicated that the resulting drainage was neutralised rather than acidic. This geochemical signature is typical of neutral mine drainage or mine-influenced saline groundwater rather than AMD.

Fe and Mn concentrations varied between bores, with peaks in Fe and Mn at MB93–MB94 corresponding to periods of higher sulfate, while Al remained consistently low (<0.2 mg/L). Minor short-term increases in Cu, Co, Ni, and Zn were also recorded in MB93–MB94 between 2018 and 2020, but these were not associated with a decline in pH or systemic metal enrichment. Moderate increases in As and Mo at some sites likely reflected natural geochemical mobilisation under oxidising–neutral conditions.

Collectively, the groundwater data indicated a well-buffered system where oxidation–neutralisation reactions dominated over acid generation. The chemistry was defined by elevated sulfate and EC, stable pH and alkalinity, low Al, and moderate Fe–Mn variability—all consistent with neutralised AMD.

Summary

Across both surface water and groundwater environments within the Cadia Hill Pit area, there was no evidence of net AMD. The observed patterns—circumneutral pH, persistent alkalinity, elevated sulfate and EC, and generally low Fe, Al, and trace metal concentrations, are consistent with NMD, where sulfide oxidation has occurred but acidity was neutralised by carbonate buffering reactions.

While the sulfate and EC trends suggested some influence of mine-related oxidation and groundwater–surface water interaction, the neutral pH and stable metal behaviour indicated effective geochemical control of acidity. Ongoing monitoring of key parameters (pH, alkalinity, sulfate, Al, Fe, Mn, and EC) is recommended to verify the continued stability of these neutralised conditions and to identify any future transition toward acidic drainage should buffering capacity decline.

3.2 TAILINGS STORAGE FACILITIES EASTERN ZONE

The evaluation included time-series data for key AMD indicators across surface water sites (CAWS42, CAWS43, and CAWS60) and groundwater bores (MB68–MB70, MB20, MB21, MB69, and MB80).

Surface Water

Across the TSF Eastern Zone surface water sites, pH values remained within the circumneutral to mildly alkaline range (approximately 6.5–8.0) for the duration of the monitoring record. Bicarbonate alkalinity was consistently present and typically high (often exceeding 200 mg/L as $CaCO_3$), indicating a strong buffering capacity within the catchment. The presence of stable alkalinity and the absence of pH values below 5 confirmed that active acid generation has not occurred within surface water pathways around the TSF.

Sulfate concentrations displayed moderate variability, with generally higher levels at CAWS42 compared to CAWS43 and CAWS60. Periodic increases in sulfate were observed after 2018 and corresponded to concurrent rises in EC and TDS, with EC occasionally reaching 4,000 µS/cm. This pattern indicates limited sulfide oxidation and solute mobilisation, but under buffered conditions where carbonate reactions have neutralised any acid produced.

Fe and Al concentrations are generally low across all surface water sites, with occasional minor Fe peaks and sporadic Al increases at CAWS42. These were not accompanied by pH decline or multi-metal enrichment, suggesting transient mobilisation under neutral conditions rather than acid solubility. Mn concentrations were low and stable (<0.2 mg/L), further supporting the absence of redox instability or acidic mobilisation.

Trace metal concentrations (including Cu, Zn, Ni, Co, As, Mo, and Se) showed minor variability, with localised increases in As, Mo, and Zn at CAWS42 during recent years. However, these remained within ranges typical of neutral to mildly alkaline drainage and likely related to groundwater discharge or tailings seepage influence rather than AMD. Overall, the surface water chemistry indicated neutralised mine drainage conditions rather than acidic drainage, with geochemical control exerted by carbonate buffering and limited sulfide oxidation.

Groundwater

Groundwater data from TSFEZ bores show consistent circumneutral pH (typically 6–8) and positive alkalinity throughout the monitoring period, with no evidence of net acidity or acid generation. Bicarbonate alkalinity is particularly high in bores MB70, MB21, and MB20, reflecting significant buffering from carbonate-bearing materials in the subsurface. The sustained neutral pH across all monitoring points confirms that the groundwater system remains geochemically buffered and not acidified.

Sulfate concentrations in groundwater exhibited a moderate upward trend in bores MB21 and MB20, with values up to ~1,000 mg/L, coinciding with elevated EC (up to 7,000 µS/cm) and TDS (>4,000 mg/L). These trends align with minor oxidation of sulfide-bearing materials or contact with tailings seepage but under neutralised conditions. The consistent pH and strong alkalinity indicate that any acidity generated is effectively neutralised prior to discharge, producing NMD rather than acidic AMD.

Fe and Mn concentrations were variable among bores, with Fe reaching up to ~10 mg/L and Mn up to ~1 mg/L in MB21 and MB20 during mid-monitoring years. Al concentrations remained generally low (<0.3 mg/L). The Fe–Mn enrichment appears to have resulted from redox-driven mobilisation under sub-oxic conditions rather than acid leaching. There was no concurrent increase in Al or decrease in pH, confirming that these metals are being released under neutral conditions.

Trace metals including Cu, Zn, Ni, and Co displayed occasional short-term elevations in MB20 and MB21 but lacked correlation with pH or sulfate excursions. As and Mo were moderately elevated in several bores, consistent with natural mobilisation from mineralised strata under neutral to alkaline conditions. Overall, the groundwater geochemical signature showed elevated sulfate and EC but stable pH, positive alkalinity, low Al, and variable Fe–Mn—characteristic of neutral mine drainage or mine-influenced saline groundwater, not AMD.

Summary

Both surface water and groundwater within the TSFEZ area exhibited circumneutral pH, positive alkalinity, and elevated sulfate and EC consistent with NMD conditions. The geochemical evidence indicates that sulfide oxidation processes may be occurring at a limited scale, but the generated acidity was neutralised through carbonate buffering reactions. There was no indication of persistent low pH, acidity, or co-elevated Fe–Al–trace metal signatures that would typify active net AMD.

While sulfate enrichment and elevated EC in certain bores (notably MB20 and MB21) suggested some influence of tailings seepage or mine-derived groundwater, these waters remained well-buffered and non-acidic. The TSFEZ system therefore represents a neutralised, sulfate-rich drainage environment rather than an acid-generating one. Continued monitoring of pH, alkalinity, sulfate, EC, Fe, Mn, and Mo is recommended to confirm ongoing geochemical stability and to provide early detection of any future transition toward acidification if buffering capacity diminishes.

3.3 TAILINGS STORAGE FACILITIES WESTERN ZONE

A review of long-term surface water and groundwater quality data (2013–2024) for the Tailings Storage Facility Western Zone (TSFWZ) was undertaken to assess whether AMD or Neutral Mine Drainage NMD processes were occurring.

Surface Water

Surface water quality across TSFWZ sites (CAWS61–CAWS68, CAWS72, CAWS75–CAWS76) was characterised by circumneutral to mildly alkaline pH (typically between 6.5 and 8.5) throughout the entire monitoring record. Bicarbonate alkalinity was consistently present, ranging from 100–400 mg/L as $CaCO_3$, confirming effective buffering capacity and neutralising potential. There were no instances of sustained pH below 5.5, which would indicate active net acid generation.

Sulfate concentrations vary moderately across sites, generally between 200 and 1,000 mg/L, with corresponding increases in EC (ranging up to 5,000 µS/cm) and TDS. The parallel elevation of these parameters indicated a solute loading influence from oxidation of sulfide-bearing materials or seepage from tailings, though under conditions where acidity was neutralised. The persistently neutral pH and high alkalinity confirmed that sulfate enrichment occurred under net neutral mine drainage conditions rather than acidic AMD.

Fe and Al concentrations were generally low, with Fe rarely exceeding 2 mg/L and Al typically below 0.6 mg/L. Small, transient peaks observed between 2015–2018 were not associated with corresponding pH decline, suggesting redox variation or colloidal transport rather than acid solubility. Mn showed moderate concentrations (up to 0.4 mg/L) at some sites but remained stable or decreased through time.

Among the trace metals, Cu, Zn, Ni, and Co displayed isolated increases between 2017 and 2020, especially at CAWS62 and CAWS68. However, these trends were not concurrent with changes in pH or alkalinity and likely reflected localised water–rock interaction or tailings seepage, rather than AMD processes. Mo concentrations were notably elevated (up to ~0.8 mg/L) at some sites but under neutral to alkaline pH conditions, suggesting mobilisation by oxidation which was buffered. Overall, surface water chemistry in the TSFWZ was indicative of neutralised drainage with elevated sulfate and metals under stable pH conditions, not active AMD.

Groundwater

Groundwater from TSFWZ monitoring bores (MB18, MB23–MB25, MB24, MB26–MB29A, MB84–MB90) also exhibited circumneutral pH (typically 6.0–8.0) and consistently positive alkalinity values. No sustained episodes of acidic pH or negative alkalinity were observed across the record. The groundwater therefore remained well-buffered against acid generation, indicating that carbonate and silicate minerals were actively neutralising any acidity produced during sulfide oxidation.

Sulfate concentrations were moderate to high (ranging between 300 and 1,200 mg/L) in several bores (particularly MB77A, MB79, MB84, and MB86) and closely correlated with EC (3,000–7,000 µS/cm) and TDS (2,000–5,000 mg/L). These elevated ionic concentrations reflected minor mine-water influence or saline groundwater discharge rather than net AMD formation. Despite high sulfate and EC, the neutral pH and measurable alkalinity confirmed that acid generated from sulfide oxidation was neutralised before discharge, producing neutral mine drainage.

Fe and Mn showed localised increases, with Fe reaching up to ~2.5 mg/L and Mn up to ~2 mg/L in some bores during 2016–2019. However, Al concentrations remained consistently low (<0.3 mg/L), suggesting redox-driven Fe and Mn mobility under neutral conditions rather than acid-solubility mechanisms. These Fe–Mn peaks were typical of groundwater systems influenced by minor redox cycling rather than AMD.

Trace metals such as Cu, Zn, Ni, and Co showed short-lived increases between 2017 and 2020, primarily at bores MB24–MB25 and MB86–MB87, but lacked co-occurrence with decreasing pH or high Al. Mo and As displayed moderate enrichments under neutral to mildly alkaline conditions, consistent with oxidative release from mineral phases in buffered systems. The geochemical trends across the bore network therefore represented a stable, well-buffered system, with sulfate enrichment reflecting tailings seepage or water–rock interaction rather than unbuffered acid leachate.

Summary

The combined surface water and groundwater data for the TSFWZ area provide no evidence of net AMD. Both systems showed stable circumneutral pH, persistent alkalinity, but elevated sulfate and EC under buffered conditions. Iron and aluminium remained low, and Fe–Mn or trace metal variations were minor and not indicative of substantial acid mobilisation.

The results indicated that NMD was the dominant process within the TSFWZ. Sulfide oxidation occurred in limited zones, but carbonate minerals neutralised the acidity produced, maintaining neutral to alkaline pH and preventing AMD formation. The geochemical trends suggested that the current drainage regime was stable and effectively controlled by natural buffering mechanisms within the tailings and surrounding materials.

Continued monitoring of pH, alkalinity, sulfate, EC, Fe, Mn, and Mo is recommended to confirm the persistence of neutralised conditions and to provide early detection of any potential shifts toward acidification should the buffering capacity diminish over time.

3.4 TAILINGS STORAGE FACILITIES SOUTHERN ZONE

The analysis included time-series data for pH, alkalinity, sulfate, EC, TDS, and dissolved metals for surface water sites (CAWS41, CAWS42, CAWS30, CAWS54–CAWS56, CAWS59, and CAWS63) and groundwater bores (MB26A–MB29A, MB68, MB77A–MB83).

Surface Water

The surface water pH remained stable and circumneutral (ranging between approximately 6.5 and 8.0) throughout the monitoring period across all sites. Bicarbonate alkalinity and total alkalinity were consistently positive, typically exceeding 200 mg/L as $CaCO_3$ at several locations, confirming a persistent buffering capacity and the absence of net acid generation. There were no recorded instances of pH falling below 5.0, indicating that net acidification processes were not occurring within surface water pathways of the TSFSZ.

Sulfate concentrations showed moderate elevation and variability between sites, with the highest values recorded at CAWS41 and CAWS55 (up to ~1,200 mg/L), corresponding with increases in EC and TDS. EC values ranged between 1,000 and 3,000 µS/cm and mirrored sulfate fluctuations, suggesting that solute loadings were derived from sulfide oxidation or tailings seepage influence. However, as these increases occurred under circumneutral pH and persistently positive alkalinity, they were interpreted as evidence of NMD rather than acidic drainage.

Concentrations of Fe and Al were generally low, with occasional short-term increases in Fe (up to ~2 mg/L) and Al (up to ~3 mg/L) in early monitoring years. These sporadic elevations were not accompanied by declining pH or co-elevations in other metals, suggesting transient redox effects or suspended particulates rather than AMD mobilisation. Mn remained low (<0.3 mg/L) and stable across all sites.

Trace metal concentrations including Cu, Zn, Ni, Co, As, and Mo displayed limited variation, with As and Mo showing mild increasing trends at some locations (e.g., CAWS55 and CAWS42) after 2018. These changes likely reflected neutral to alkaline geochemical conditions facilitating oxyanion mobility rather than acid leaching. Overall, surface water chemistry indicated a neutralised system dominated by sulfate and major ions, with no evidence of net AMD generation.

Groundwater

Groundwater data from the TSFSZ also demonstrated circumneutral pH (typically 6–8) and consistently positive alkalinity across all bores. Bicarbonate alkalinity values remained high, particularly at MB79, MB77A, and MB83, confirming significant buffering potential. There were no periods of sustained low pH or negative net acidity in any of the monitoring records.

Sulfate concentrations showed moderate to strong elevation in several bores, with MB77A, MB78, and MB79 recording values between 600 and 1,200 mg/L during 2016–2020. These increases corresponded with elevated EC (up to 3,000 µS/cm) and TDS (>2,000 mg/L), suggesting the presence of mine-influenced or saline groundwater. Despite these elevated sulfate and salinity levels, the persistence of circumneutral pH and positive alkalinity indicated effective neutralisation of any acidity produced through sulfide oxidation, characteristic of neutral mine drainage conditions.

Fe concentrations were variable, with occasional increases up to 9 mg/L at MB77A and MB78, while manganese ranged up to 0.8 mg/L at similar locations. Al remained low (<0.3 mg/L) throughout the dataset. The Fe–Mn enrichment pattern, unaccompanied by low pH or elevated Al, suggested redox-controlled mobilisation under neutral to sub-oxic conditions rather than acid-driven solubility.

Trace metals (Cu, Zn, Ni, and Co) showed minor, short-term fluctuations across several bores but without systematic correlation with pH or sulfate variations. As and Mo exhibited slightly elevated concentrations under neutral to alkaline pH conditions, consistent with natural desorption or tailings contact under oxidising–neutral groundwater chemistry. These geochemical signatures were typical of mine-influenced groundwater systems where oxidation and neutralisation occurred concurrently, preventing the development of net AMD.

Summary

Both surface water and groundwater datasets from the TSFSZ area showed no evidence of net AMD. pH and alkalinity values remained consistently neutral to mildly alkaline, with sulfate and EC elevations occurring under well-buffered conditions. Iron and aluminium were generally low, and variations in Fe–Mn or trace metals were minor and not indicative of acid leaching.

The observed sulfate enrichment and salinity patterns reflected ongoing oxidation–neutralisation reactions, where sulfide minerals were oxidised but acidity was neutralised by carbonate and silicate buffering within the TSF and surrounding sediments. This produced NMD rather than acidic drainage.

The overall geochemical stability within the TSFSZ indicated that current management and containment systems were effective in mitigating net AMD generation. Continued monitoring of sulfate, EC, Fe, Mn, and alkalinity is recommended to ensure early detection of any geochemical changes that could reduce buffering capacity and lead to acidification over time.

3.5 ORE PROCESSING AREA

The evaluation included time-series data for key AMD indicators across surface water sites CAWS73, CAWS78, and CAWS79, representing the OPA area.

pH values across all three sites remained within a circumneutral to mildly alkaline range (6.5–8.2), with no evidence of sustained acidity (pH <5.5) throughout the record. Both bicarbonate and total alkalinity were consistently measurable, confirming the presence of remaining carbonate buffering capacity. These stable and positive alkalinity levels indicated that acid generation was being effectively neutralised, and there was no indication of net acidity or loss of buffering over time.

Sulfate concentrations were moderate to elevated across all sites, particularly at CAWS73, where values periodically exceed 1,000 mg/L. Similar temporal increases were found for EC and TDS, which rose in parallel with sulfate. The positive correlation between these parameters suggested ongoing sulfide oxidation contributing dissolved ions to solution; however, the persistence of neutral pH and measurable alkalinity indicates NMD rather than net acid AMD was produced.

Concentrations of Fe, Al, and Mn showed periodic increases (notably at CAWS79 around 2017–2019) but remained generally below levels indicative of acid leaching. Cu, Zn, and Ni exhibited moderate concentrations with minor variability, while As and Mo showed gradual increases at CAWS73, likely reflecting natural or mine-related geochemical mobilisation under neutral to oxidising conditions. The absence of co-elevated Fe–Al–trace metals, typical of AMD plumes, supports an interpretation of neutralised mine drainage or saline groundwater interaction rather than active AMD.

Summary

The OPA surface water sites exhibited neutral pH, consistent alkalinity, and moderate sulfate enrichment coupled with stable metal concentrations, all indicative of NMD rather than AMD. The water chemistry reflected ongoing sulfide oxidation that was effectively buffered by carbonate minerals, preventing net acid generation. Slightly elevated sulfate, EC, and selected metals (Mo, As, Mn) suggested mine-influenced neutral drainage, but not net acidic or environmentally detrimental conditions.

3.6 WASTE ROCK DUMPS

The evaluation included time-series data for key AMD indicators across surface water sites CAWS73, CAWS78, and CAWS79.

pH values across all three sites remained within a circumneutral to mildly alkaline range (6.5–8.2), with no evidence of sustained acidity (pH <5.5) throughout the record. Both bicarbonate and total alkalinity were consistently measurable, confirming the presence of carbonate buffering capacity. These stable and positive alkalinity levels indicated that acid generation was being effectively neutralised, and there is no indication of net acidity or loss of buffering over time.

Sulfate concentrations are moderate to elevated across all sites, particularly at CAWS73, where values periodically exceeded 1,000 mg/L. Similar temporal increases were observed for EC and TDS, which rose in parallel with sulfate. The positive correlation between these parameters suggested ongoing sulfide oxidation contributing dissolved ions to solution; however, the persistence of neutral pH and measurable alkalinity indicates NMD rather than net acid AMD resulted.

Concentrations of Fe, Al, and Mn showed periodic increases (notably at CAWS79 around 2017–2019) but remained generally below levels indicative of acid leaching. Cu, Zn, and Ni exhibited moderate concentrations with minor variability, while As and Mo showed gradual increases at CAWS73, likely reflecting natural or mine-related geochemical mobilisation under neutral to oxidising conditions. The absence of co-elevated Fe–Al–trace metals, typical of AMD plumes, supported an interpretation of NMD or saline groundwater interaction rather than net AMD.

Summary

The WRD surface water sites exhibited neutral pH, consistent alkalinity, and moderate sulfate enrichment coupled with stable metal concentrations, all indicative of NMD rather than AMD. The water chemistry reflected ongoing sulfide oxidation that was effectively buffered by carbonate minerals, preventing acid generation. Slightly elevated sulfate, EC, and selected metals (Mo, As, Mn) suggested mine-influenced neutral drainage, but not net acidic or environmentally detrimental conditions.

3.7 BLAYNEY DEWATERING FACILITY

The evaluation included time-series data for key AMD diagnostic indicators across surface water sites NEC061 and NEC062, located in the BDF area.

Both NEC061 and NEC062 displayed consistently circumneutral pH (6.5–8.0) across the entire record, with no evidence of acidic excursions. Bicarbonate and total alkalinity were measurable throughout and remained within a stable range, suggesting strong carbonate buffering capacity and the absence of net acidity. These results confirmed that acid generation processes were not active at either site.

Sulfate concentrations remained moderate (typically <250 mg/L) and displayed only minor temporal variation. EC and TDS followed similar stable patterns, with EC values mostly below 800 µS/cm. The lack of sharp increases or strong correlations between sulfate and EC implied that oxidation of sulfide minerals was limited and that any sulfate released was being neutralised or diluted within the local hydrological system.

Fe, Al, and Mn concentrations remained low and near the detection limits for most of the monitoring period, with occasional peaks (notably Mn up to ~1.5 mg/L at NEC061 around 2017). However, these fluctuations occurred under neutral pH and measurable alkalinity, suggesting redox-driven metal mobilisation rather than acid leaching. Cu and Zn showed mild variability but no sustained elevation, while As and Mo exhibited low levels consistent with background. The absence of co-elevated Fe–Al–trace metals supported a non-acidic, stable hydrochemical regime.

Summary

Water quality at the BDF sites was characterised by neutral pH, positive alkalinity, low sulfate, and generally low metal concentrations, with only minor temporal variability. These characteristics indicated no evidence of AMD. Instead, the geochemical conditions were consistent with NMD or natural background variability within a buffered system.

3.8 CADIA DEWATERING FACILITY

The evaluation included time-series data for key AMD diagnostic parameters across surface water sites CDW03, CDW04, and CDW05, located within the Cadia DWF.

Across all sites, pH values remained circumneutral to mildly alkaline (6.8–8.3), showing little variation over time. Bicarbonate and total alkalinity were consistently measurable and moderately elevated (typically 100–250 mg/L as $CaCO_3$), indicating a strong buffering capacity and the absence of net acidity. There were no recorded instances of pH depression (<5.5) or alkalinity depletion, confirming that net acid drainage processes were not active in the DWF–Cadia system.

Sulfate concentrations were relatively low (<120 mg/L) and stable throughout the monitoring period. EC and TDS values (300–1,000 µS/cm) showed minor temporal variability, with no clear upward trend indicative of increasing solute load. The co-variation between sulfate, EC, and TDS suggested limited sulfide oxidation under well-buffered conditions. These patterns were consistent with neutralised or background drainage chemistry rather than active AMD.

Metal concentrations were generally low across all parameters. Fe and Al exhibited occasional increases (notably at CDW03 around 2019–2020) but remained well below levels typical of acid leaching environments. Mn showed moderate variability with peak values up to ~0.5 mg/L but no sustained enrichment trend. Cu and Zn showed scattered detections within low mg/L range, while As and Mo remained low and stable, with Mo showing minor gradual increases consistent with neutral–alkaline mobilisation processes. The absence of concurrent Fe–Al–trace metal enrichment confirmed non-acidic mobilisation mechanisms.

Summary

The Cadia DWF surface water sites exhibited neutral pH, stable alkalinity, and low sulfate and metal concentrations, characteristic of NMD or natural background drainage under buffered conditions. Slight temporal variability in Fe, Mn, and Cu reflected natural redox or hydrological influences rather than acid generation.

4.

CONCLUSION AND RECOMMENDATIONS

4.1 CONCLUSION

A comprehensive review of long-term (2010–2024) water quality data for surface water and groundwater sites across the CVO was undertaken to evaluate the potential occurrence of AMD or related neutralised drainage processes. The assessment integrated trends in pH, alkalinity, sulfate, EC, TDS, and dissolved metals including Fe, Al, Mn, Cu, Zn, Ni, Co, As, Mo, Sb, and Se, using time-series plots and hydrochemical interpretation.

Across all monitoring zones, pH values remained circumneutral to mildly alkaline (≈6.5–8.5) with consistently measurable alkalinity, confirming the persistence of carbonate buffering and the absence of net acidity. No sites exhibited sustained low pH (<5.5) or high acidity, which would indicate net acid generation.

While sulfate, EC, and TDS were elevated at several downstream and tailings-associated sites—particularly CAWS65, CAWS73, and MB93–MB94—these occurred under neutral to alkaline conditions, reflecting net production of NMD not AMD.

Metal concentrations (Fe, Al, Mn, Cu, Zn, Ni, Co, As, Mo) were generally low or showed declining trends, with no co-elevation of Fe–Al–trace metals typical of AMD plume development. Transient peaks (e.g., Mn at MB93–MB94 and CAWS79; Cu and Mo at CAWS65 and CAWS73) appeared linked to localised redox variability, mine-influenced recharge, or neutral–alkaline dissolution processes, rather than acid solubility. The presence of Mo enrichment under neutral to alkaline conditions further supported this interpretation.

Overall, the integrated dataset provided no evidence of net AMD at any surface water or groundwater monitoring location across the CVO site. The dominant geochemical regime is NMD, where sulfide oxidation occurs but acid generation is counteracted by effective carbonate buffering. The system appears hydrogeochemically stable, with gradual improvement or stabilisation in water quality trends since approximately 2018.

4.2 RECOMMENDATIONS

1. Ongoing Monitoring and Trend Analysis

   - Maintain regular monitoring of key diagnostic parameters: pH, alkalinity, sulfate, EC, Fe, Al, Mn, and Mo, supported by periodic review of trace metals (Cu, Zn, Ni, Co, As, Sb).
   - Continue using time-series and correlation analyses to track long-term trends and detect early deviations indicative of changing oxidation or buffering dynamics.

2. Buffering Capacity and Neutralisation Assessment
   - Periodically assess alkalinity and acid-neutralising capacity (ANC) relative to sulfate and dissolved metal concentrations to ensure carbonate buffering remains effective.
   - Consider geochemical modelling (e.g., PHREEQC or GWB) to simulate equilibrium relationships and predict future trends under variable oxidation–neutralisation scenarios.
3. Targeted Investigations
   - Investigate localised sulfate and metal enrichments (notably at CAWS65, CAWS73, MB93–MB94, and CAWS79) to confirm sources and delineate neutralised drainage pathways.
   - Where practical, incorporate isotopic or mineralogical analyses (e.g., S or O isotopes in sulfate) to confirm oxidation mechanisms and distinguish between natural background and mine-derived inputs.
4. Adaptive Management
   - Integrate AMD/NMD risk assessment outcomes into the broader water management and rehabilitation planning framework for CVO.
   - Should alkalinity show signs of long-term decline or sulfate increase be observed, consider adaptive management measures such as passive neutralisation systems, controlled drainage routing, or alkaline amendment of reactive zones.
5. Reporting and Data Integration
   - Include AMD indicator analyses as a regular component of CVO's annual water quality reporting.
   - Ensure data continuity and inter-site comparability by standardising laboratory methods, detection limits, and metadata recording.

5.

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